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The variable geometry central receiver system concept. First results and comparison with conventional central receiver systems

Ruiz, Valeriano^a; Frasquet, Miguel^{b*}; Martínez, Fernando^b; Silva, Manuel^a; Lillo, Isidoro^a; Díaz Andrades, Francisco^b; Lobo Márquez, Gonzalo^b

^a*Thermodynamics and Renewable Energies Group, School of Engineering, University of Seville. Camino de los Descubrimientos s/n, 41092 Seville, Spain*

^b*Centro Tecnológico Avanzado de Energías Renovables (CTAER), Paraje de los Retamares s/n; 04200 Tabernas (Almería), Spain*

Abstract

In line with the global trend for improving efficiency of existing solar power plants, the CTAER has developed and built a variable geometry central receiver facility, in which the solar field rotates around the tower axis following the sun's position during the day. The goal of this new approach is to increase the optical efficiency of the field by significantly reducing the angle of incidence of the Sun on the heliostats. This paper presents the advantages of this new variable geometry design and describes the main features of the experimental facility based on this approach as built by CTAER in Almería. It also compares a conventional solar central receiver plant (i.e., with stationary heliostats and receiver) and an equivalent variable geometry power plant. For this study we employed published data from a real solar central receiver plant with known production (Abengoa's PS10). The results of the study show an increase in annual energy collection and distribution by the variable geometry plant, leading to a potential reduction in the number of heliostats required compared to a conventional central receiver plant for the same annual energy collection.

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1. Introduction

The relationship between the energy that finally arrives at the receiver and the available solar energy, which depends mainly on the location of the power plant, is called optical efficiency. Given a certain rated receiver thermal power, the necessary solar field size depends primarily on this parameter. Therefore, an

increase in optical efficiency translates into a reduction in the solar collection surface required. Considering that the solar field represents roughly 40% of the total cost of a central receiver power plant [1], this reduction can affect the final cost of power generated significantly.

In designing central receiver solar fields, the heliostats are located in positions where the optical efficiency of the field is highest. As the position with maximum efficiency is not stationary, but varies with the position of the Sun, the position to be selected is assumed to be the one with the best efficiency integrated over one year. However, it is possible to achieve improvements in performance from this traditional approach if the position of the heliostats in the field varies during the year, always seeking the position of maximum efficiency at every instant. One way to do this is to rotate the solar field following the Sun's path.

There are different theoretical proposals based on this approach [2-3], but to date no such facility had ever actually been built. The experimental facility built by the CTAER in Tabernas (Almeria) is the first and only one of its kind, and has made it possible to go from theoretical concept to as-built reality [4] with everything this implies.

This paper describes the advantages of this approach, which has been baptized "variable geometry". First, two fields, one stationary and one rotating, are compared from a theoretical viewpoint without the limitations of construction. Then they are compared from a practical point of view, in which the characteristics of construction and operation are considered. These characteristics could be defined thanks to the experience acquired by the CTAER in the construction of its Tabernas facility.

Nomenclature

η_{opt}	optical efficiency	$f_{int}(x, y, t)$	intercept factor
$f_{\cos\theta}(x, y, t)$	cosine factor	$f_{sb}(x, y, t)$	shading and blocking factor
$f_{at}(x, y)$	atmospheric attenuation factor		

2. Optical efficiency in solar fields

2.1. Traditional approach

The optical efficiency of a heliostat located at a given position within the solar field (x,y), at a given instant of time (t), is calculated as follows:

$$\eta_{opt}(x, y, t) = \rho \times f_{\cos\theta}(x, y, t) \times f_{at}(x, y) \times f_{int}(x, y, t) \times f_{sb}(x, y, t) \quad (1)$$

Where ρ is the reflectance of the heliostat surface, which depends on the material and the type of mirror construction; $f_{\cos\theta}$, called the cosine factor, depends on the heliostat position and the time of study; f_{at} is the atmospheric attenuation factor, which depends mainly on the distance of the heliostat from the receiver and ambient conditions; f_{int} is called the intercept factor, which includes the amount of energy incident on the receiver or aperture of the cavity it is housed in related to the amount reflected by the field, less attenuation. This factor depends on the position of the heliostat and the time of study; f_{sb} is the

factor that describes radiation loss from blocking and shading among heliostats before it arrives at the receiver. This factor depends on the position of the heliostat and the time of study.

At the time of solar field design, when the position of each heliostat is evaluated, it must be recalled that the factors on which optical efficiency depends often follow opposite tendencies. For example, in a very compressed field where the heliostats are relatively close to the tower, there is significant loss from shading and blocking, but spillage, complement to 1 of the intercept factor, and atmospheric attenuation would not be very significant. However, when the field is more spacious, the heliostats are farther from the tower and from their neighbors, and therefore, shading and blocking losses are lower. This is not so for attenuation and spillage. From a purely energy point of view, the final configuration of the field is a balance of all the factors which maximize the optical efficiency and therefore, the energy that arrives at the receiver.

Of all the factors on which the solar field optical efficiency depends, the cosine factor is the one with the most weight in the final result, followed by mirror reflectivity. The cosine factor varies with the angle of incidence, θ , which is the angle between the solar vector and the normal to the heliostat surface. Thus it varies almost symmetrically during the day. Losses due to the cosine factor are considerably lower at solar noon, when the field's axis of symmetry is aligned with the solar azimuth. It therefore seems possible that the cosine factor, and thereby optical efficiency, will be better if the field's axis of symmetry coincides with the solar azimuth at every instant.

2.2. Rotating field approach

To make the solar field axis of symmetry and the solar azimuth coincide at any given instant, heliostat positions must rotate following the Sun's path at all times. Therefore, at dawn, the solar field would be located west of the tower, at solar noon, it would be located north of the tower (similar to a conventional field) and at sunset, to the east of the tower. If during this movement of the solar field the receiver remains immobile, at sunrise and sunset, when the solar field is at extreme locations (west and east, respectively) there would be significant spillage, since the projection of the heliostat image on the receiver would be very oblique. To avoid this, the receiver must also rotate following the solar path.

The theoretical concept of a rotating power plant is therefore: A solar field that rotates following the Sun's path to improve the cosine factor, and a receiver which also rotates to reduce spillage from excessive oblique incidence on the receiver. Although at first it seems that this approach achieves significant increases in the optical efficiency of the solar field, the rest of the factors optical efficiency depends on must also be evaluated to find out its true overall influence.

3. Theoretical comparison of a rotating central receiver solar plant and a conventional one

A comparison of the influence of the factors which optical efficiency depends on in a rotating plant and a conventional one is given below. For this comparison, the basic configuration selected is similar to the PS10 commercial solar power plant [5]. Two cases are studied, both with the same basic configuration. "Case 1" is a conventional central receiver solar plant with stationary heliostats. "Case 2" is the same plant but under the theoretical approach described above, where the heliostats and the receiver rotate following the Sun's path. In this study, no limitations of construction or operation were considered, so the position of each heliostat moves in a circular path with the tower at the center, and it does this at the same speed as the variation in the solar azimuth. The calculations for this study were done using MIRVAL, ray-tracing software developed by Sandia Labs [6].

3.1. Cosine factor

The cosine factor is calculated as the cosine of the angle of incidence, which is defined as the angle formed by the solar vector and the normal to the heliostat surface. The wider the angle of incidence is, the higher cosine factor losses are. The cosine factor may be represented as the relationship between available power and power resulting after the angle of incidence is projected on the heliostat plane:

$$f_{\cos\theta} = \frac{DNI \cdot S_h \cdot \cos(\theta)}{DNI \cdot S_h} \quad (2)$$

where DNI is the direct normal irradiance and S_h is the net surface of the heliostat. The angle of incidence of each heliostat depends on its position and the time of day. In a conventional field, “Case 1”, the heliostats located in the middle of the field have a nearly symmetrical performance and the maximum variation in the angle of incidence is relatively low. Performance of the heliostats on the edges of the field is far from symmetrical, showing a minimum/maximum near sunrise and sunset depending on its position in the field. The maximum variation in the angle of incidence for extreme heliostats is very high.

In a rotating field, “Case 2”, the heliostats face the Sun with the same relative azimuth all day long, which makes the variation in the angles of incidence smooth out considerably. Figure 1 shows the cosine factor in both cases for a heliostat in the center (16) and another on the edge (411), for three characteristic times of the year.

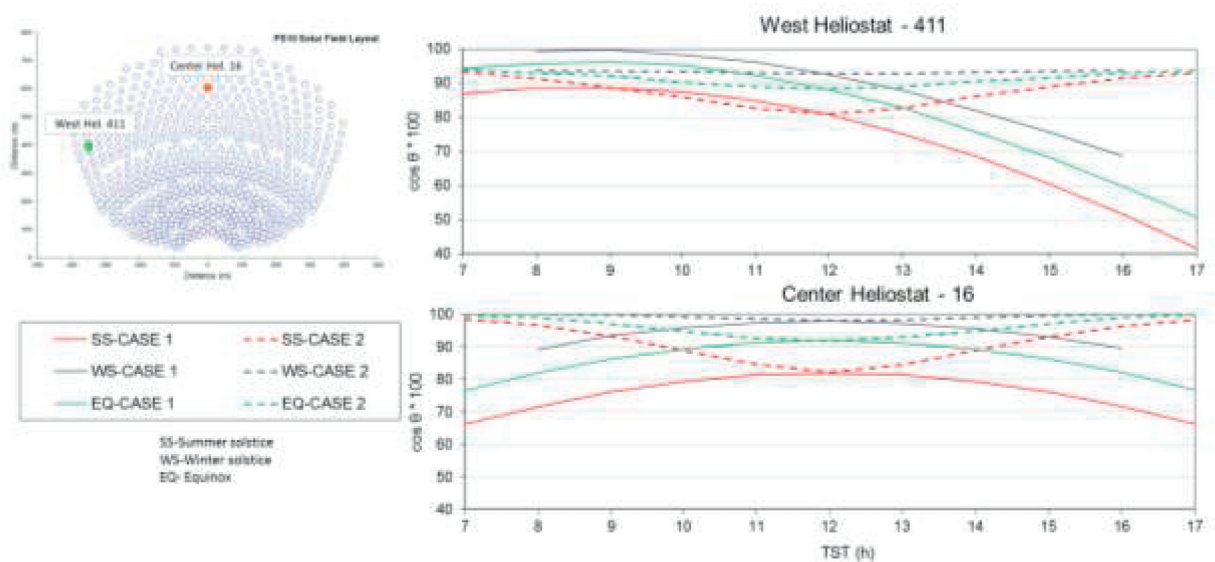


Figure 1: Variation in the cosine factor of a heliostat on three characteristic days of the year. Case 1 is shown with a solid line and Case 2 with a dashed line.

Considerable improvement is found in both heliostats, and this is more significant in the heliostat on the edge of the field. The annual influence of the cosine factor, calculated by integrating all the plant's heliostats over one year, is summarized in Table 1, showing 7% less loss in Case 2.

Table 1

Annual influence of the cosine factor

CASE 1	0.874
CASE 2	0.940

3.2. Reflectance

This study does not consider the angular influence of reflectance, which will be the subject of future work, so its effect in optical efficiency is similar in both cases.

3.3. Atmospheric attenuation

Atmospheric attenuation depends on ambient conditions and distance of the heliostat from the tower. These factors are similar in both Cases 1 and 2, so they do not cause any difference in optical efficiency.

3.4. Shading and blocking

Heliostat losses from blocking and shading (S&B) depend on the position of the Sun and its relative position with regard to neighboring heliostats. A common configuration in central receiver solar field designs is the radial staggered layout. This distribution, where the heliostats alternate positions, each group of three forming equilateral triangles, has been shown to provide good field density without high losses [7].

In a conventional field with a staggered geometry, the lowest losses from shading and blocking are at solar noon on any day of the year, where the axis of symmetry coincides with the solar.

In a rotating field, the axis of symmetry is always aligned with the solar azimuth so the percentage of shading could be expected to be constant and lower all day long. However, as seen in Figure 2, the general tendency is similar to the conventional case, where the minimum occurs at solar noon and there are maximums at sunrise and sunset. These peaks very early and very late in the day are because the Sun is so much lower in the sky at those times that a staggered layout cannot avoid shading. In fact, losses are aggravated since the only row that is not shaded is the first one. It may be observed in **¡Error! No se encuentra el origen de la referencia.2** that early and late in the day, losses from S&B are slightly higher in rotating plants than in the conventional ones.

Table 2 shows the annual influence of shading and blocking in both cases. Indeed, there are more losses in the rotating plant, although the difference is less than 2% per year.

Table 2

Annual influence of the shadow and blocking

CASE 1	0.930
CASE 2	0.913

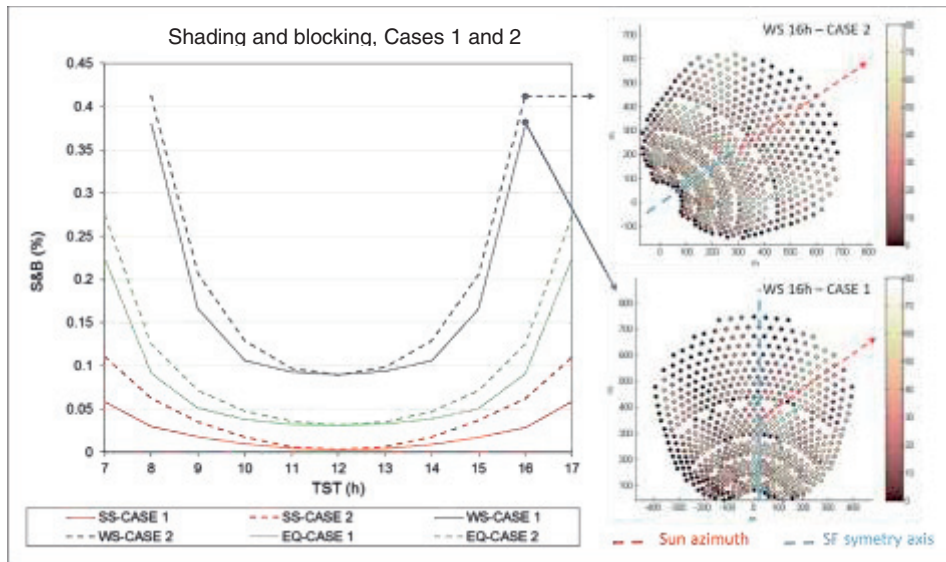


Figure 2: Comparison of the S&B factor in Cases 1 and 2. On the right, S&B distribution at 1600 h for Cases 1 and 2.

3.5. Spillage

Spillage is the power entering the receiver zone, but not entering the aperture. In both cases, field orientation with regard to the normal to the receiver is similar, since in “Case 2”, the receiver is also rotating. Therefore, there are no differences between the two cases due to oblique projection on the receiver. However, at any given instant, the size of the images may differ in the two cases because of the increased size of the image due to astigmatic aberration.

Astigmatic aberration is a type of optical aberration that occurs when a heliostat operates at angles of incidence over zero, which produces an increase in the size of the Sun’s image projected onto the central receiver.

The size of the image produced by a spherical mirror at a given slant range depends mainly on the size of the heliostat, the angle of incidence and the subtended angle of the Sun. Assuming a spherical heliostat approach, the focal distance (F) is equivalent to half of the curvature radius (r) of the spherical surface.

$$F = r/2 \quad (3)$$

And assuming that the heliostat is focused on the receiver, the focal distance is equivalent to the slant range (d).

$$F = d \quad (4)$$

The height of the image on the receiver may be expressed by the following equation: [8]

$$h = 2 \cdot D_t \cdot \sin^2(\theta/2) + \beta_s \cdot r/2 \quad (5)$$

where D_t is the size of the mirror on the tangential plane, θ is the angle of incidence and β_s is the subtended angle of the Sun. The first term represents the contribution of the collimated axial beam to image height, and the second term represents the contribution of the collimated non-axial beam produced by the finite angular size of the Sun. Similarly, image width is given by:

$$w = 2 \cdot D_s \cdot \sin^2(\theta/2) + \beta_s \cdot r/2 \quad (6)$$

where D_s is the size of the mirror on the sagittal plane.

Except for the angle of incidence, the rest of the factors that the size of the distorted image depends on are similar in both cases, so any difference in size of image between the two cases depends exclusively on the angle of incidence. In Section 3.1, it was shown how in Case 2, the rotating plant, the angles of incidence were significantly reduced, so aberration, and thereby potential spillage, is also lower in this case than in the conventional central receiver solar plant in Case 1.

The adimensional ratio of aberration, which represents the relationship between the size of the distorted solar image and the ideal, was used to check the difference in size of the images in the two cases.

$$h/(\beta_s d) \text{ or } w/(\beta_s d) = (2/\beta_s F_r) \sin^2(\theta/2) + 1 \quad (7)$$

where $F_r = d/D$ represents the focal ratio. The relationship of how many times larger the image in Case 1 is than Case 2 may be found by dividing the adimensional ratio of aberration in Case 1 and the adimensional ratio of aberration in Case 2.

$$\frac{h/(\beta_s d)_{CASE1}}{h/(\beta_s d)_{CASE2}} \text{ or } \frac{w/(\beta_s d)_{CASE1}}{w/(\beta_s d)_{CASE2}} \quad (8)$$

¡Error! No se encuentra el origen de la referencia. Figure 3 shows this relationship for the height (width, which would be equivalent, is omitted here due to lack of space) for the heliostats studied in Section 3.1. Logically, the increase in size of the distorted images follows the same tendency as the angle of incidence in Figure 1: Variation in the cosine factor of a heliostat on three characteristic days of the year. Case 1 is shown with a solid line and Case 2 with a dashed line.

1. For the heliostats on the edges of the solar field early and late in the day, the image on the receiver is almost twice the size as the one in the rotating plant. In the center heliostats, a rotating plant would substantially reduce the size of the image except at solar noon, where the image would be the same size as in Case 1.

3.6. Optical efficiency

Although the influence of each of the factors that optical efficiency depends on has been shown separately, the performance of the whole must be evaluated to be able to come to an overall conclusion. Table 3 gives the annual optical efficiency in each case. It may be seen that the annual optical efficiency in Case 2 is 3.4 percentage points higher than in Case 1.

Table 3

Annual optical efficiency

CASE 1	0.646
CASE 2	0.680

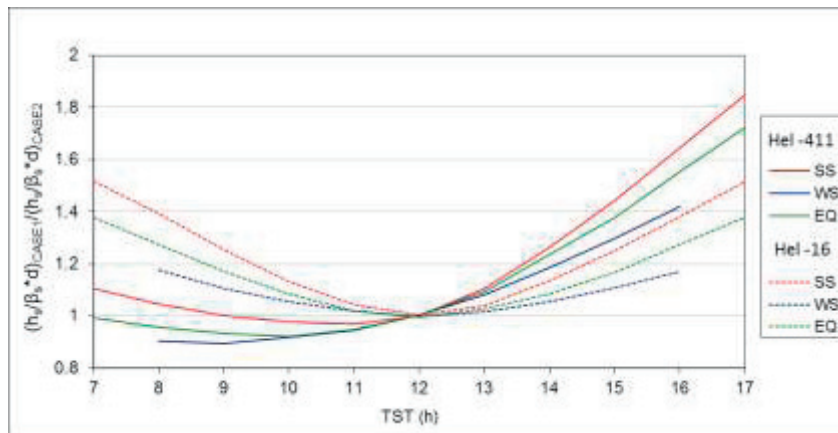


Figure 3: Relationship between the heights of the image projected by Heliostat 16 for Case 1 and Case 2 on 3 characteristic days of the year

4. Practical comparison of a rotating central receiver solar plant and a conventional one

There are different construction solutions for transferring the theoretical concept of the rotating fields to a real solar power plant. [2] proposes locating the heliostats and the tower in fixed positions on a platform, and the whole platform rotates. This approach requires turning the whole solar field, which is not very practical for large commercial plants. [3] proposes using single-axis-tracking heliostats mounted on rails and a stationary receiver with movable secondary reflectors. This approach reduces the need for the rotating surface in the other concept, but mounting heliostats with single-axis tracking makes it almost impossible to keep aiming on the receiver constant. The use of secondary reflectors complicates receiver design and causes greater losses due to the reflectivity of these mirrors.

The CTAER has built a pilot facility in Tabernas based on the concept called “variable geometry”, which makes use of concentric rails on which the heliostats move angularly on a specially designed moving carriage. This way only one rail has to be built for each row of heliostats in the field design. The rails must be perfectly circular and concentric to the tower. The conversion of the study solar field to a variable geometry field is shown in Figure 4. The heliostats are two-axis tracking and are moved around the track by a moving carriage. The pedestal of the heliostat is screwed to the carriage by a flanged joint so any commercial heliostat can be mounted in the plant. The moving carriage is a 4x4 m² metal structure with cylindrical wheels, two on the inner rail and two on the outer rail. Movement is by an electric motor that drives the two front wheels of the heliostat. As shown above, the receiver must also rotate. The CTAER variable geometry facility has a galvanized steel tower the top of which houses a 4 m-diameter bearing. This bearing makes it possible for the top of the tower (receiver platform) to rotate.

The optical performance of a variable geometry field is similar to the rotating field described in Section 3. The difference is the individual results from heliostat to heliostat, since obviously, they occupy different positions in the theoretical concept and the as-built solution. The conclusions arrived at from the detailed optical efficiency analysis of the rotating field are completely extrapolable to a variable geometry

field, and it is therefore unnecessary to repeat the detailed analysis of the factors on which optical efficiency depends.

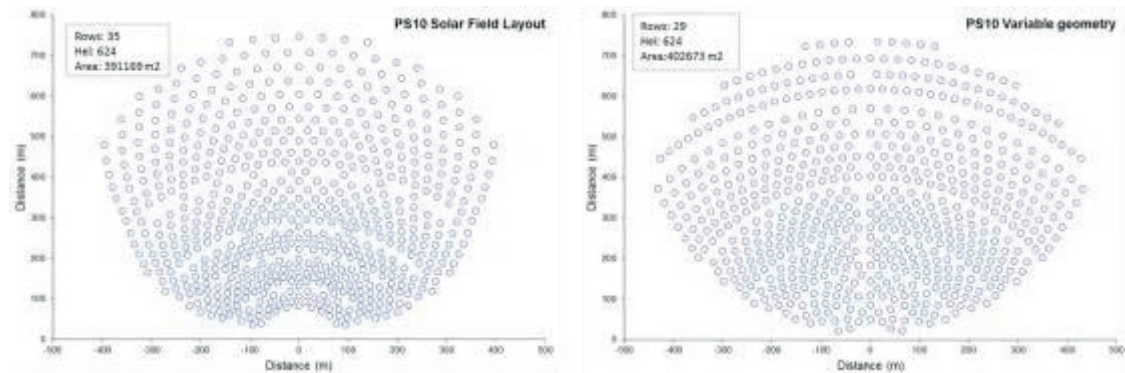


Figure 4: Left, PS10 solar field. Right, the same field using the variable geometry concept

In this case, a complete annual study carried out (see Figure 5), found that the variable geometry plant (VGP) produces 8.753% more thermal energy annually in the receiver aperture than the stationary plant (SP). Translating this increase in energy to the number of heliostats necessary, the variable geometry configuration would require 14% fewer heliostats than a conventional PS10-type plant to produce the same annual energy.

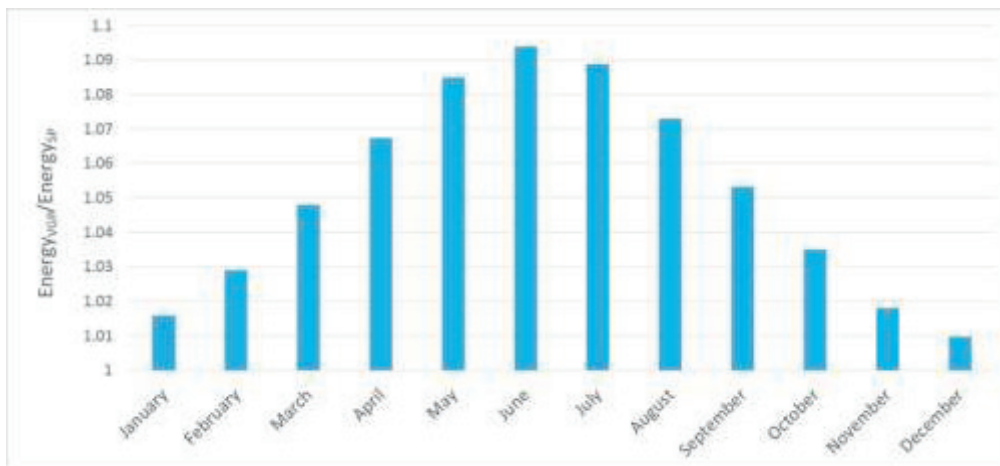


Figure 5: Monthly distribution of the relationship of energy between the variable geometry and conventional cases

5. Conclusions

There are several advantages to optical efficiency when the axis of symmetry remains aligned with the solar azimuth at all times. For this, the heliostats have to rotate following the Sun's path. This theoretical concept presents significant advantages for the cosine factor and spillage because of the reduction in the

angle of incidence. It has a slight disadvantage in shading and blocking, mainly at the earliest and latest hours of the day because the staggered geometry accentuates shading when the Sun is lowest in the sky. The rotating field has no additional advantage or disadvantage for atmospheric attenuation and reflectivity. Altogether, a field with this concept improves optical efficiency by 3.4% over a conventional field.

When the theoretical concept is transferred to the reality of construction, certain technical limitations of the state-of-the-art and economic feasibility have to be taken into account. The CTAER proposal called “variable geometry” places the heliostats on concentric circular tracks around the tower. This solution, already proven under real-scale conditions in the CTAER facility in Tabernas, has the same advantages as the theoretical concept of rotating fields and its implementation is feasible with current state-of-the-art.

The increase in optical efficiency, and thereby, of the thermal energy that arrives at the receiver in a variable geometry plant, is significantly higher than a conventional central receiver system where the heliostats and the receiver are stationary. In the example under study, where the commercial PS10 plant layout has been redesigned using the variable geometry concept, an improvement of 8.573% over the conventional solar central receiver plant was achieved. This variable geometry plant would also require 14% fewer heliostats than a conventional Abengoa PS10-type plant.

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